MAE263F Project Midterm Report

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I. Introduction

Robot manipulation has long been dominated by rigid-link manipulators that achieve high precision and repeatability in structured environments such as manufacturing and assembly lines. These systems rely on well-defined kinematic and dynamic models to perform tasks with millimeter-level accuracy. However, their rigidity becomes a limitation in unstructured or dynamic environments, particularly where interaction with delicate or irregular objects is required. In contrast, soft robotic manipulators, composed of highly deformable materials such as silicone or elastomers, can passively adapt their shape to external forces, allowing for safer and more flexible interaction. The study of soft manipulators remains an ongoing research topic due to several challenges, such as difficulty of achieving accurate sensing and control for unknown environment. Despite these challenges, soft robotic manipulation has demonstrated promising applications in diverse fields such as minimally invasive surgery, agricultural harvesting, and marine exploration, where adaptability and gentle contact are paramount.

II. Motivation

This project focuses on developing and simulating a soft robotic manipulator for underwater exploration, mounted in front of a submarine. The manipulator will perform tasks such as environmental monitoring, sample collection, and interaction with fragile marine organisms like corals or sponges. Traditional rigid arms are limited in such settings due to their inability to safely contact or adapt to irregular surfaces and their sensitivity to hydrodynamic disturbances. In contrast, a soft manipulator's compliance allows it to absorb fluid-induced forces and conform to its surroundings, making it inherently safer and more stable for trajectory tracking under uncertainty. The use of soft manipulators in underwater exploration could significantly enhance the precision and safety of data collection and specimen sampling, contributing to sustainable ocean research and reducing ecological damage during exploration missions.

The proposed system consists of a soft robotic manipulator mounted on a submarine, designed to maintain its end-effector position while the vehicle is stationary. Hydrodynamic forces generated by the flow field act on the manipulator, causing deformation and positional drift. The control objective is to maintain the desired end-effector position by actively adjusting the base of the robot connected to the vehicle, similar to an inverted pendulum stabilization problem. The manipulator operates in an uncertain underwater environment affected by random disturbances such as local flow turbulence, gusts, and collisions with small obstacles. This setup represents a complex nonlinear control problem where the compliant structure must counteract fluid-induced motion while preserving trajectory stability and precision. Addressing these challenges requires accurate modeling of both the manipulator's elasticity and the external flow dynamics, as well as a robust control strategy capable of compensating for continuous disturbances.

III. Literature Review

Control of a soft robotic appendage is a well-studied challenge, with multiple simulation approaches developed to predict motion under external forces and control inputs. There is a model of a soft appendage using a planar discrete elastic rod to analyze its swinging motion around a fixed point [1]. The hybrid control design used separate controllers for upward equilibrium stabilization and for driving the appendage back into position. While the model operated in air and ignored fluid dynamics, the control strategy offers valuable insights for stabilization in dynamic environments. The present project extends this concept into an underwater setting, where hydrodynamic forces dominate. Instead of stabilizing a static equilibrium, the goal is to maintain the end-effector position under continuous flow disturbances, emphasizing continuous feedback control rather than hybrid switching.

Similarly, another model used a planar discrete elastic rod to simulate eel-like underwater locomotion [2]. This work introduced internal damping and explored various hydrodynamic modeling approaches but assumed a stationary fluid. In contrast, the proposed system will operate within time-varying ocean currents, requiring stabilization under external flow disturbances. Although this study focuses on locomotion rather than manipulation, it provides useful insights into underwater dynamics and the impact of fluid–structure interactions, which are directly applicable to the proposed underwater manipulator.

Many applications propose utilizing pneumatic or hydraulic actuation for controlling the robot to take advantage of the soft links [3] [4]. This will lead to novel actuation methods for the robot where each node in a discrete elastic rod model can be actuated. This leads to an extension where the proposed study can look at the effects of disturbances on a manipulator in motion.

In the most fascinating paper, a neural controller can be used to abstract the minutiae of a control algorithm [5]. The main model used will still be a discrete elastic rod in a

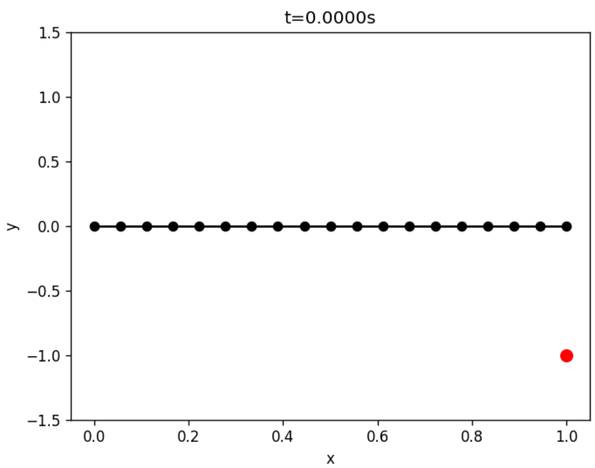

Fig. 1. Initial Setup of the Simulation with Target Location.

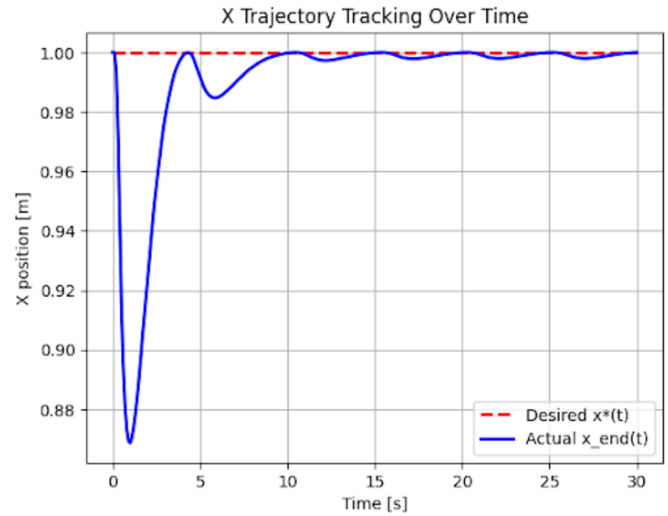

Fig. 2. Appendage End Trajectory in the X-Direction with No External Loads.

manner similar to that proposed in the paper. Combining the novel actuation methods presented in previous papers with the control optimization methods for deformable linear objects in this paper, there can be an extension looking into integrating a neural control scheme to have the appendage move to a target location under load.

IV. Progress

A. Simulation Environment

This project is approached in progressive stages. The first stage focuses on validating the simulation environment and ensuring appropriate controller behavior within a viscous medium. The soft rod is modeled as a discrete elastic rod consisting of 19 nodes, each with a radius of 0.15 m, resulting in a total rod length of 1 m. EcoFlex 00-30 was selected as the rod material due to its mechanical properties, which closely resemble those of human skin [6].

The material density is computed using the specific gravity provided in the datasheet, where

$$\rho = (\text{specific gravity}) \times \rho_{\text{water}} = 1.07 \times 1000 \ = 1070\,\text{kg/m}^3.$$

Since the datasheet does not provide a direct value for Young's modulus, we approximate it using the reported 100% modulus. The 100% modulus for EcoFlex 00-30 is given as 10 psi, which we convert to SI units as

$$E = 10\,\text{psi} = 68947.6\,\text{Pa}.$$

The rod dynamics are simulated in two dimensions using a spring-based formulation that includes both stretching and bending elements. To simulate an actuated soft robotic appendage, the system is programmed with two degrees of freedom: one linear actuation along the Y-axis and one revolute actuation about the Z-axis. A PID controller is used to control these degrees of freedom, regulating the rod's motion toward a set target position.

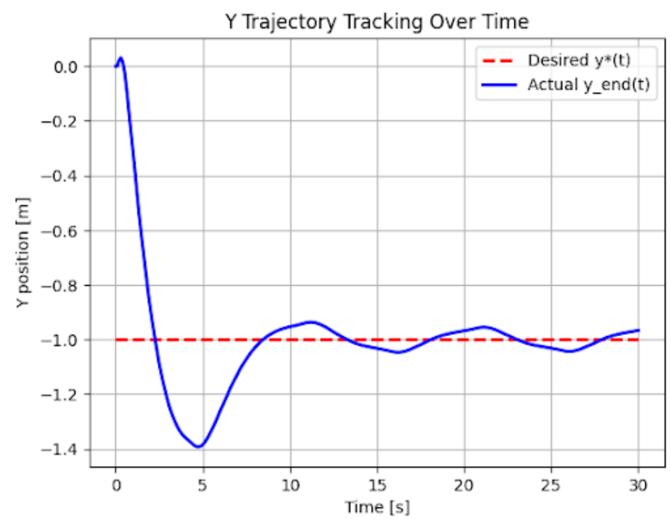

Fig. 3. Appendage End Trajectory in the Y-Direction with no External Loads.

To evaluate the no-load condition, the rod is initially placed at rest, with the first node positioned at the origin $(0, 0)$. The setup for this test is illustrated in Figure 1. The red marker in the figure denotes the target position, which in this example is set to $(1, -1)$. This target was chosen to observe the rod's natural behavior as it moves through the viscous water environment without external loading, thereby demonstrating its passive dynamic response.

The results of the position tracking tests are presented in Figures 2 and 3, which show the appendage tip trajectories in the X- and Y-directions against time. Both plots indicate that the PID controller is able to guide the soft rod toward the desired target location with stable convergence and minimal overshoot.

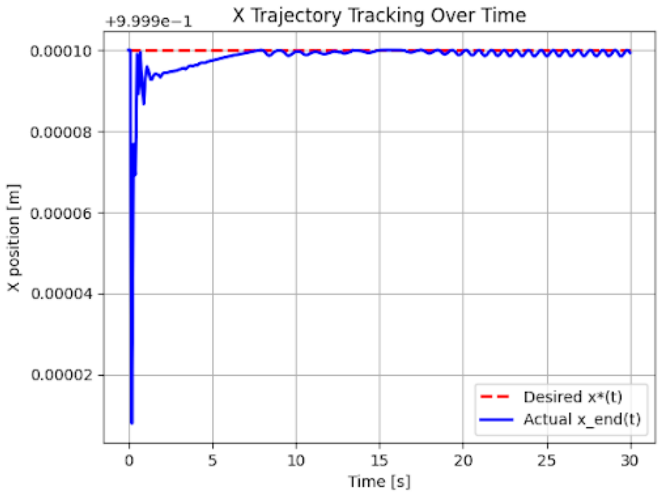

Fig. 4. Appendage End Trajectory in the X-Direction using Low Reynold Number Loading.

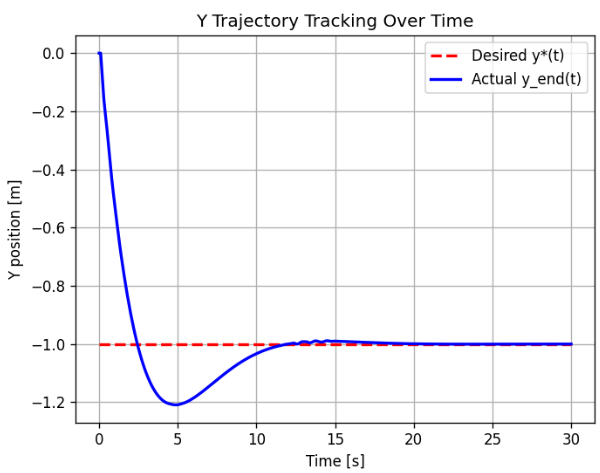

Fig. 5. Appendage End Trajectory in the Y-Direction using Low Reynold Number Loading.

B. Low Reynolds Number Environment

With the simulation framework and controller validated under no-load conditions, a low Reynolds number hydrodynamic model was incorporated to more accurately represent underwater behavior, particularly in environments characterized by linear flow or minimally turbulent ocean regions.

The resulting trajectory tracking performance under low Reynolds number flow conditions is shown in Figures 4 and 5. In the x-direction, a small oscillatory response appears near steady state likely due to the interaction between the controller and viscous drag; however, its magnitude is minimal and does not affect overall tracking performance. The y-direction response converges smoothly, showing that the controller performs well in a predominantly linear background flow. Together, these results confirm that the system behaves as intended in underwater conditions, providing a more realistic

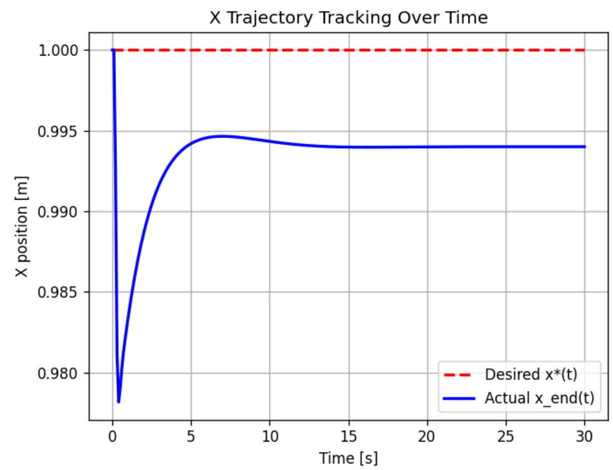

Fig. 6. Appendage End Trajectory in the X-Direction using High Reynold Number Loading.

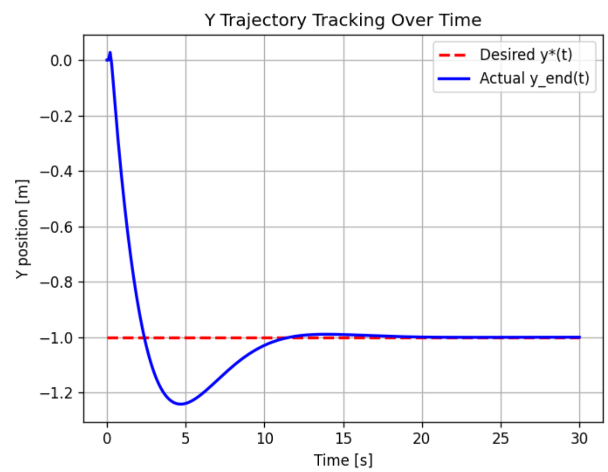

Fig. 7. Appendage End Trajectory in the Y-Direction using High Reynold Number Loading.

representation than the no-load case.

C. High Reynolds Number Environment

The trajectory tracking performance under high Reynolds number loading is shown in Figures 6 and 7. In this environment, inertial effects become significant, providing a better representation of more turbulent or fast-moving underwater flow. The x-direction response exhibits a noticeable overshoot and does not converge to the intended position. This occurs because, in an inertia-dominated regime, the appendage's motion is strongly influenced by accumulated momentum, causing delayed and exaggerated deformations. Since there is no direct actuation in the x-axis, these deformations cannot be corrected by the controller, preventing the tip from reaching the desired x-coordinate. In contrast, the y-direction performance remains stable, with the trajectory converging smoothly and with minimal oscillations, demonstrating that the controller is still effective along the actuated axis even under high Reynolds number conditions.

V. Next Steps

The first step moving forward is to improve the convergence properties of the simulation and implement explicit control in the x-direction. While the current controller regulates motion primarily along the y-axis, adding actuation or corrective feedback in the horizontal direction will be essential for accurately stabilizing the appendage, particularly in environments where deformation prevents passive convergence.

The next major step is to extend the simulation to handle non-uniform flow fields. The present model assumes flow along a single axis; however, real underwater environments exhibit spatially varying currents and disturbances acting in multiple directions. Deep-water currents typically move on the order of centimeters per second, whereas surface currents can be orders of magnitude faster and significantly more unstable. To simulate these conditions, the study will incorporate multi-directional, time-varying flow profiles using high Reynolds number loading to replicate the turbulence and inertial effects present in such environments.

With more realistic hydrodynamic loading established, the simulation will be expanded into three dimensions, introducing gravity and buoyancy along the z-axis. In 3D, non-uniform currents will induce twisting and out-of-plane deformation along the appendage, requiring an additional degree of freedom for full maneuverability. The planned approach is to introduce a revolute joint in the x-direction between the existing linear and revolute joints, enabling a spherical workspace that can be translated through the linear actuator.

Finally, once stability is achieved under these additions, the system will be extended to explore alternative control schemes and more advanced end-effector manipulation strategies. While the current work models a soft appendage mounted on a mobile base, a true soft robotic manipulator would require distributed deformation control along its full length. Although this represents the most complex enhancement to the framework, it is expected to provide the greatest improvement in precision, robustness, and stabilization capability.

References

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